MOISTURE-DEPENDENT PHYSICAL PROPERTIES OF CHIA (*Salvia hispanica* L.) SEEDS

E. N. Guiotto, V. Y. Ixtaina, M. C.Tomás, S. M. Nolasco

ABSTRACT. *The dependence of physical properties of dark and white chia seeds on moisture content (MC) was determined in moisture ranges of 4.6% to 17.7% and 4.9% to 16.2% dry basis (d.b.), respectively. The length, width, thickness, geometric diameter, and specific surface area increased linearly from 1.91 to 2.07 mm, 1.24 to 1.34 mm, 0.81 to 0.87 mm, 1.24 to 1.34 mm, and 4.85 to 5.67 mm^2 for dark seeds and from 1.92 to 2.07 mm, 1.26 to 1.32 mm, 0.81 to 0.86 mm, 1.25 to 1.33 mm, and 4.94 to 5.56 mm^2 for white seeds, respectively. Seed volume, equivalent diameter, and thousand seed mass ranged from 1.09 to 1.31 mm^3, 1.28 to 1.36 mm, and 1.230 to 1.352 g for dark seeds and from 1.02 to 1.25 mm^3, 1.25 to 1.34 mm, and 1.170 to 1.293 g for white seeds, respectively, with the increase in MC. True density diminished from 1.115 to 1.025 g cm^{-3} and from 1.144 to 1.028 g cm^{-3} for dark and white seeds, respectively. Bulk density, porosity, and static coefficient of friction were assessed for dark seeds. Bulk density decreased from 0.713 to 0.644 g cm^{-3}, while the porosity values varied polynomially. The static coefficient of friction on galvanized iron and aluminum increased from 0.25 to 0.34 and from 0.26 to 0.34, respectively. Results showed that seed MC affected the physical properties studied for both types of seeds.*

Keywords. *Moisture content, Physical properties,* Salvia hispanica *L. seed.*

Chia (*Salvia hispanica* L.), an annual herbaceous plant belonging to the Lamiaceae or Labiatae family, is native to southern Mexico and northern Guatemala. In pre-Columbian Mesoamerica, the crop of this species was a major commodity and its seeds were valuable for food, medicine, and oil. As it was associated with medicinal and religious practices, its cultivation was banned by Spanish conquerors and replaced by exotic crops, such as wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (Cahill, 2003). Nowadays, this crop is being reintroduced to western diets to improve human health because it is an important source of omega-3 fatty acids, antioxidants, dietary fiber, protein, vitamins, and minerals.

Chia seed is traditionally consumed in Mexico, the southwestern U.S., and South America, but it is not widely known in Europe. However, in 2009, the European Union approved chia seeds as a novel food, allowing them to comprise up to 5% of a bread product's total matter (Commission of the European Communities, 2009).

Chia has been cultivated in environments ranging from tropical to subtropical conditions. Plants are not very frost tolerant, but they can be grown as summer annuals in greenhouses in some parts of Europe (Huxley, 1992). Today, chia is mostly grown in Mexico, Bolivia, Argentina, Ecuador, Australia, and Guatemala, and it has been demonstrated that the species has great potential as a future crop plant (Coates and Ayerza, 1996).

The seed yield ranges between 500 and 600 kg of seeds ha^{-1}; however, up to 2500 kg ha^{-1} could be obtained under experimental conditions based on irrigation and fertilization (Coates and Ayerza, 1996). The Ord Valley in Western Australia was the main producer of chia seeds worldwide in 2008, with a planted area of 750 ha and a growing prospect of 1700 ha for 2009 (Brann, 2008).

Chia seed is an oilseed that differs from other oilseeds in the acidic composition of its oil, with high levels of essential polyunsaturated fatty acids (omega-3 and omega-6) and a low percentage of saturated fatty acids (~10%). The oil yield of chia seeds varies between 32% and 38% of extractable oil by weight and contains the highest known natural level of α-linolenic acid (C 18:3) (61% to 70%) and an important content of linoleic acid (C 18:2) (15% to 21%), which varies according to different environmental factors, such as temperature, light, and soil type. Several research studies have reported the nutritional benefits of chia with respect to other natural sources of these essential fatty acids, e.g., menhaden fish, seaweed, and flax (Ayerza and Coates, 2005; Ixtaina, 2007). Table 1 shows the chemical composition of chia seed (Ixtaina et al., 2010).

S. hispanica populations that are commercially grown today consist mostly of dark seeds, but there are cultivars with a very low percentage of white seeds, a qualitative characteristic determined by the presence of a single recessive

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Table 1. Chemical composition of chia seed (Ixtaina et al., 2010).

Component	Content (% d.b.)
Protein	29
Lipids	32
Ash	5
Fiber	27
Carbohydrates[a]	7

[a] Calculated by difference.

Figure 1. Photographs of a commercial pool chia seeds (4×).

gene (Cahill and Provance, 2002). Chia seeds are shown in figure 1.

Knowledge of the physical properties of agriculture materials is very important for post-harvest operations as well as for the design of processing equipment (Mohsenin, 1970). The physical properties affect the conveying characteristics of solid materials by air or water. Size, shape, and physical dimensions of chia seeds are important in sizing, sorting, and other separation processes. Knowledge of the bulk and true densities of chia seeds is necessary to design equipment for processing and storing, such as dryers and bins. Porosity also affects the resistance to airflow through bulk seeds. The coefficient of static friction plays an important role in transport and storage of seeds.

Moisture-dependent physical properties have been reported for different types of seeds. However, no published literature was found on the relationship between physical properties of chia seeds and their moisture content (MC). Chia seeds were analyzed only for an average moisture content of 7.0% (d.b.) (Ixtaina et al., 2008).

The objective of this study was to investigate some moisture-dependent physical properties of dark and white chia seeds, namely length, width, thickness, true and bulk density, porosity, volume, thousand seed mass, equivalent and geometric diameter, specific surface area, sphericity, and static coefficient of friction against galvanized iron and aluminum in the moisture range from 4.6% to 17.7% d.b.

MATERIALS AND METHODS

VEGETABLE MATERIAL AND SAMPLE CONDITIONING

The present study was carried out using 20 kg of chia seeds (*S. hispanica*) obtained from commercial sources in Salta, Argentina (25° S, 65.5° W), that were kept in their original package (hermetically sealed 1 kg polyethylene bags) at 5°C. We manually cleaned the seeds to remove all foreign matter, such as stones, dirt, and broken seeds. In this way, a randomized sample of chia seeds (about 2 kg) was picked by a sample splitter (CPASA, Centro Proveedor Agropecuario, Buenos Aires, Argentina). The seeds were manually separated according to their white or dark pericarp surface. Each type of seed was further divided into six or seven groups of samples. One group was maintained at the initial moisture conditions, while the other groups were either hydrated or dried to obtain the desired moisture content. To vary the MC of a sample, we dried (convection air oven, 40°C to 45°C) a predetermined quantity of chia seeds to the desired MC. Higher MCs were reached indirectly through saturation of the atmosphere in contact with the seeds. For this purpose, we placed a small, clean, dry vessel with seeds into a container with 100 cm^3 of water, which was then hermetically sealed for 36, 168, or 240 h. We determined the MC of seeds by the standard method that is used for rapeseed (*ASAE Standards*, 1999) in a forced oven at 130°C ±1°C for 4 h.

PHYSICAL PROPERTIES

We assessed the physical properties of seeds at all moisture levels, as described below.For determining the average size of the seeds, we randomly picked a sample of 100 seeds for each coat color and MC, and then we measured their three linear dimensions, namely length (L), width (W), and thickness (T), using a digital micrometer reading at 0.01 mm. We calculated the geometric mean diameter (D_g) of chia seeds using the following relationship (Gupta and Das, 1997):

$$D_g = (LWT)^{1/3} \tag{1}$$

We determined the specific surface area (S) of chia seeds assuming an ellipsoidal shape of the seed and calculated it according to equation 2 (Altuntaş et al., 2005):

$$S = \pi D_g^2 \tag{2}$$

We investigated the average bulk density (ρ_b) of dark chia seed at seven different moisture levels using the standard test weight procedure (Singh and Goswami, 1996) by filling a circular container of 90 cm^3 volume with seeds from a height of 15 cm at a constant rate of approximately 1.5 cm s^{-1} and then weighed the content. We performed these measurements in triplicate.

We determined the average true density (ρ_t) as a function of MC by liquid displacement using a pycnometer of 50 ±0.1 cm^3 capacity, fitted with a calibrated thermometer graduated in divisions of 0.1°C and with a side-arm and cap (Mohsenin, 1970), using toluene (C_7H_8; $\rho = 0.867$ g cm^{-3}) as a solvent to prevent water absorption in the seeds during the experiment. The volume of toluene displaced was found by immersing a weighed quantity of chia seed in the toluene (Singh and Goswami, 1996). We performed these measurements in triplicate for both types of seeds.

We determined the packing porosity (ε) of dark chia seed at the different MCs from bulk and true densities using the relationship given by Thompson and Isaacs (1967) and Mohsenin (1970) as follows:

$$\varepsilon = \left(\frac{(\rho_t - \rho_b)}{\rho_t} \right) \times 100 \tag{3}$$

We determined the seed volume (V) for each color using the following relationship given by Özarslan (2002):

$$V = \left(\frac{m}{\rho_t} \right) 10^3 \qquad (4)$$

where m is the unit mass of the seed (g) determined in samples used to calculate the true density.

We calculated the equivalent diameter (D_e) and sphericity (ϕ) for both types of chia seeds using equation 5 (Gupta and Das, 1997) and equation 6 (McCabe et al., 1986), respectively:

$$D_e = \left(\frac{6V}{\pi} \right)^{1/3} \qquad (5)$$

$$\phi = \left(\frac{D_e}{L} \right) \times 100 \qquad (6)$$

To determine the mass of a thousand seeds (W_{1000}), we weighed 100 randomly selected seeds with an analytical balance (0.0001 g accuracy) and then extrapolated this mass to 1000 seeds. This process was repeated 30 times (Ixtaina et al., 2008).

We measured the static coefficient of friction for dark chia seeds at different MCs for two structural materials, namely galvanized iron and aluminum. These materials are commonly used for transport, storage, and handling operations of grains, pulses, and seed and for building storage and drying bins. We filled a hollow PVC cylinder (50 mm diameter, 50 mm high, open at both ends) with seed samples and placed the cylinder on an adjustable tilting table. We raised the cylinder about 2 mm above the base of the bulk seed so as not to touch the surface and tilted the surface gradually by means of a screw device until the seed-filled cylinder started to slide down the slope (Singh and Goswami, 1996). We read the angle of tilt (α) on a graduated scale and calculated the friction coefficient using the following relationship:

$$\mu = \tan \alpha \qquad (7)$$

where μ is the coefficient of friction, and α is the angle of tilt (degrees). We replicated the static coefficient of friction reading ten times for each of the MCs studied.

STATISTICAL ANALYSIS

We analyzed the results for statistical significance using one-way ANOVA, the mean comparison using Tukey's test ($p \leq 0.05$), and the regression curves between MC of seeds and physical properties using Statgraphics Plus for Windows (Statgraphics, 1999).

RESULTS AND DISCUSSION

The commercially sourced chia seeds were 89% dark seeds and 11% white seeds by mass, with an initial MC of 10.0% and 10.9% d.b., respectively. The different MCs of dark seeds obtained after sample conditioning were 4.6%, 6.5%, 8.7%, 12.0%, 15.3%, and 17.7% (d.b.), while 4.9%, 5.7%, 6.4%, 7.9%, and 16.2% (d.b.) were the corresponding levels for the white seeds. These moisture levels were selected according to the conditions usually applied in harvesting and most processing operations of grains (Sing and Goswami, 1996). The mean values of the L, W, T, D_g, and S of dark and white chia seeds at different MCs are presented in tables 2 and 3, respectively.

Averages of the three principal dimensions at different MCs were L_d = 1.97 mm, W_d = 1.29 mm, and T_d = 0.84 mm for dark chia seeds and L_w = 1.99 mm, W_w = 1.28 mm, and T_w = 0.83 mm for white seeds without significant differences ($p > 0.05$) between the two types of seeds. These results are similar to those reported by Ixtaina et al., (2008), who observed that the longitudinal dimensions (L) of dark and white chia seeds were similar.

The ANOVA detected significant differences ($p \leq 0.05$) between different moisture levels for each principal dimension in both types of seeds. Experimental values showed a linearly increasing tendency between the dimensions (L, W, and T, mm) and MC (x, % d.b.). This can be expressed by the following equations:

$$L_d = 1.8468 + 0.0117x$$
$$(\mathrm{R}^2 = 0.9848,\ p \leq 0.005) \qquad (8)$$

Table 2. Principal dimensions (L_d, W_d, T_d), geometric diameter (D_{gd}), and specific surface area (S_d) of dark chia seeds with different MCs.[a]

MC (% d.b.)	L_d (mm)	W_d (mm)	T_d (mm)	D_{gd} (mm)	S_d (mm^2)
4.6	1.91 ±0.11 a	1.24 ±0.05 a	0.81 ±0.05 a	1.24 ±0.07 a	4.85 ±0.55 a
6.5	1.92 ±0.10 ab	1.26 ±0.08 ab	0.82 ±0.04 b	1.26 ±0.06 ab	4.97 ±0.49 ab
8.7	1.95 ±0.08 bc	1.28 ±0.06 bc	0.83 ±0.04 b	1.27 ±0.06 bc	5.12 ±0.44 bc
10.0	1.96 ±0.09 bc	1.28 ±0.07 bc	0.83 ±0.04 b	1.28 ±0.06 bc	5.14 ±0.45 bc
12.0	1.98 ±0.11 cd	1.29 ±0.07 cd	0.84 ±0.04 bc	1.29 ±0.06 cd	5.24 ±0.47 cd
15.3	2.02 ±0.10 d	1.32 ±0.07 de	0.85 ±0.04 c	1.31 ±0.06 d	5.42 ±0.48 d
17.7	2.07 ±0.10 e	1.34 ±0.07 e	0.87 ±0.05 d	1.34 ±0.06 e	5.67 ±0.50 e

[a] Mean values (n = 100) ± standard deviations. Means in the same column followed by the same letter are not significantly different ($p > 0.05$).

Table 3. Principal dimensions (L_w, W_w, T_w), geometric diameter (D_{gw}), and specific surface area (S_w) of white chia seeds with different MCs.[a]

MC (% d.b.)	L_w (mm)	W_w (mm)	T_w (mm)	D_{gw} (mm)	S_w (mm^2)
4.9	1.92 ±0.06 a	1.26 ±0.03 a	0.81 ±0.02 a	1.25 ±0.02 a	4.94 ±0.18 a
5.7	1.95 ±0.07 ab	1.27 ±0.05 ab	0.82 ±0.02 ab	1.27 ±0.04 ab	5.05 ±0.30 ab
6.4	1.97 ±0.08 b	1.27 ±0.03 ab	0.83 ±0.02 b	1.27 ±0.03 ab	5.11 ±0.25 bc
7.9	1.99 ±0.08 bc	1.28 ±0.01 b	0.83 ±0.02 b	1.28 ±0.03 b	5.18 ±0.22 c
10.9	2.04 ±0.08 c	1.29 ±0.02 b	0.85 ±0.03 c	1.31 ±0.04 c	5.35 ±0.30 d
16.2	2.07 ±0.05 cd	1.32 ±0.05 c	0.86 ±0.04 c	1.33 ±0.03 d	5.56 ±0.26 e

[a] Mean values (n = 100) ± standard deviations. Means in the same column followed by the same letter are not significantly different ($p > 0.05$).

$$W_d = 1.2109 + 0.007x$$
$$(\mathrm{R}^2 = 0.9977,\ \mathrm{p} \le 0.005) \tag{9}$$

$$T_d = 0.7903 + 0.0044x$$
$$(\mathrm{R}^2 = 0.9499,\ \mathrm{p} \le 0.005) \tag{10}$$

$$L_w = 1.8780 + 0.0122x$$
$$(\mathrm{R}^2 = 0.9261,\ \mathrm{p} \le 0.005) \tag{11}$$

$$W_w = 1.2397 + 0.0049x$$
$$(\mathrm{R}^2 = 0.9965,\ \mathrm{p} \le 0.005) \tag{12}$$

$$T_w = 0.7957 + 0.0045x$$
$$(\mathrm{R}^2 = 0.9430,\ \mathrm{p} \le 0.005) \tag{13}$$

These results present a good correlation with those obtained by Deshpande et al. (1993), Özarslan (2002), Vilche et al. (2003), Abalone et al. (2004), and Altuntaş et al. (2005) for soybean, cotton, quinoa, amaranth, and fenugreek seeds, respectively.

The mean geometric diameter for the different MCs studied was 1.28 mm for dark seeds and 1.29 mm for white seeds. We found significant differences ($p \leq 0.05$) between different levels of MC for D_g (tables 2 and 3). The D_g values presented a linear increase as a function of the increased MC of 8.14% and 6.06% for dark and white seeds, respectively, according to equations 14 and 15 for both types of seeds:

$$D_{gd} = 1.2075 + 0.0057x$$
$$(\mathrm{R}^2 = 0.9698,\ \mathrm{p} < 0.005) \tag{14}$$

$$D_{gw} = 1.2273 + 0.0066x$$
$$(\mathrm{R}^2 = 0.9653,\ \mathrm{p} < 0.005) \tag{15}$$

This trend was similar to that observed for soybean (Deshpande et al., 1993), cotton (Özarslan, 2002), quinoa (Vilche et al., 2003), amaranth (Abalone et al., 2004), fenugreek (Altuntaş et al., 2005), rapeseed (Çalişir et al., 2005), and safflower (Baümler et al., 2006).

The average of the specific surface area (S) was 5.20 mm^2 for both types of seeds. The values obtained showed statistically significant differences ($p \leq 0.05$) between the different MCs (tables 2 and 3), linearly increasing 16.9% for dark and 12.5% for white seeds within the moisture content range. The increase of S may be due to a dilatation of the seeds during moisture sorption, resulting in an enhancement of the contact area.

Other researchers have observed similar behavior for soybean, amaranth, and fenugreek seeds (Deshpande et al., 1993; Abalone et al., 2004; Altuntaş et al., 2005). The relationship between specific surface area (S, mm^2) and MC (x, % d.b.) can be expressed mathematically as follows:

$$S_d = 4.5762 + 0.0584x$$
$$(\mathrm{R}^2 = 0.9809,\ \mathrm{p} < 0.005) \tag{16}$$

$$S_w = 4.7223 + 0.0538x$$
$$(\mathrm{R}^2 = 0.9647,\ \mathrm{p} < 0.005) \tag{17}$$

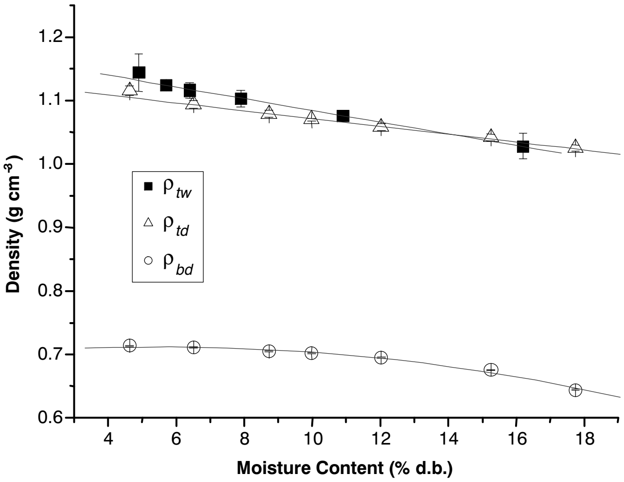

Figure 2. Effect of MC on true (ρ_{td}) and bulk density (ρ_{bd}) of dark chia seeds and true density (ρ_{tw}) of white chia seeds.

After harvesting, the seed undergoes conditioning processes (e.g., cleaning, aeration, drying, etc.) to maintain the seeds in optimal condition until their commercialization and/or processing. Knowledge of the size, surface, volume, and geometric diameter of the seeds as a function of MC is required for different handling and processing operations. In addition, this information is useful for prediction of transport and drying rates of seeds through simulations models. Figure 2 shows the increase of true density at decreasing MC for both types of seeds. This trend can be attributed to a minor volumetric contraction of the product during drying with respect to the decrease of seed mass due to water loss.

Average values of the true density of dark and white chia seeds with different MCs were 1.069 and 1.099 g cm^{-3}, respectively, with no significant differences ($p > 0.05$) between them. A similar trend was reported by Ixtaina et al. (2008). Statistical analysis of the results showed significant differences ($p \leq 0.05$) between different moisture levels for both types of seeds. The relationship between true density (ρ_t, g cm^{-3}) and the MC (x, % d.b.) of the seed can be represented by the following equations:

$$\rho_{td} = 1.1457 - 0.008x$$
$$(\mathrm{R}^2 = 0.9912,\ \mathrm{p} < 0.0001) \tag{18}$$

$$\rho_{tw} = 1.1768 - 0.0092x$$
$$(\mathrm{R}^2 = 0.9969,\ \mathrm{p} < 0.0001) \tag{19}$$

The bulk density of dark chia seeds decreased from 0.713 to 0.644 g cm^{-3} as a function of the increase of MC from 4.6% to 17.8% d.b. (fig. 2). We can explain this in terms of the enhancement in seed volume, which was greater than the increase in seed mass. The relationship between bulk density (ρ_{bd}, g cm^{-3}) and MC can be represented by the following regression equation:

$$\rho_{bd} = 0.6977 + 0.0050x - 0.0004x^2$$
$$(\mathrm{R}^2 = 0.9873,\ \mathrm{p} < 0.0005) \tag{20}$$

Regarding bulk density, chia seeds presented a behavior similar to that of cumin (Singh and Goswami, 1996) and safflower (Baümler et al., 2006) seeds.

The negative linear relationship of bulk density and true density with MC was also observed by other authors for cotton (Özarslan, 2002) and soybean (Deshpande et al.,

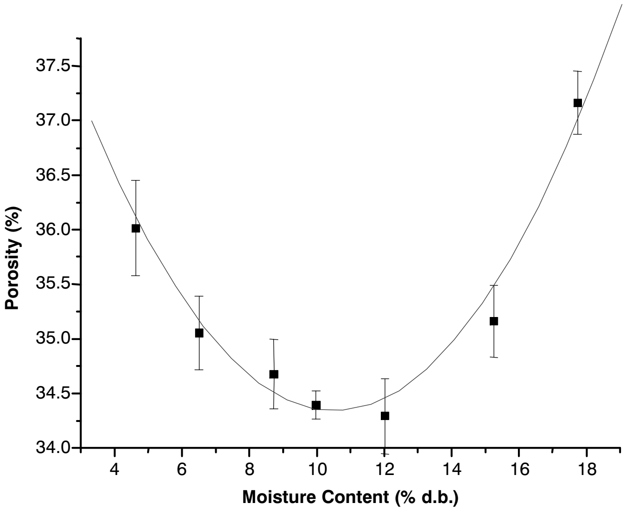

Figure 3. Effect of MC on chia seed porosity.

1993), but it was different for quinoa (Vilche et al., 2003), sunflower (Gupta and Das, 1997), and cumin seeds (Singh and Goswami, 1996), which increased linearly.

The average porosity observed for all dark samples was 35.3%, with significant differences ($p \leq 0.05$) as a function of MC. Figure 3 shows the variation of porosity (ε, %) with MC (*x*, % d.b.), with the lowest value of 34.3% occurring at MC of 12.0% (d.b.). The equation can be formulated as follows:

$$\varepsilon_d = 40.0745 - 1.0991x + 0.0049x^2$$
$$(R^2 = 0.9701,\ p < 0.0010) \qquad (21)$$

A similar trend in porosity has been reported for coriander seeds (Coşkuner and Karababa, 2007). Nevertheless, different authors observed dissimilar trends for safflower, cumin, sunflower, quinoa, and fenugreek seeds (Baümler et al., 2006; Singh and Goswami, 1996; Gupta and Das, 1997; Vilche et al., 2003; Altuntaş et al., 2005), in which porosity increased linearly with an increase in MC. However, Deshpande et al. (1993) and Özarslan (2002) observed a linear increase in porosity with a decrease in MC in soybean and cotton seeds, respectively. Since porosity depends on bulk and true densities, the magnitude of its variation depends mainly on these properties. Therefore, the porosity of each type of seed or grain could respond differently with increasing MC. This fact could be attributed to the seeds' morphological characteristics; the relative changes in their length, width, and thickness; and the associated bulk and true densities.

Taking into account the high level of polyunsaturated fatty acids, chia seeds can be easily affected by temperature. For this reason, aeration is an important process to maintain a low uniform temperature and prevent the moisture migration. The resistance to airflow or pressure drop is affected by different factors, such as the bulk density, porosity, and MC. Due to the low bulk density and size of chia seeds, the grain bed will have an important pressure drop, requiring a high level of power for driving the aeration fans.

Precision agriculture is a comprehensive system designed to optimize agriculture production through the application of crop information, advanced technology, and management practices. Using this technology, diverse approaches are used to determine the volume of the seed in storage. In order to determine the weight of the stored product, knowledge of the bulk density is relevant.

The mean values of volume were 1.21 and 1.12 mm^3 for dark and white seeds, with an increase of 20.2% and 22.9%, respectively, as a function of the rise in MC. Statistical analysis revealed significant differences ($p \leq 0.05$) between seeds with different MCs (tables 4 and 5). The variation of MC (*x*, % d.b.) and volume (*V*, mm^3) can be expressed mathematically as follows:

$$V_d = 1.0407 + 0.0156x$$
$$(R^2 = 0.9711,\ p < 0.0001) \qquad (22)$$

$$V_w = 0.9622 + 0.0189x$$
$$(R^2 = 0.9217,\ p < 0.0001) \qquad (23)$$

Deshpande et al. (1993); Özarslan (2002), Abalone et al. (2004), Altuntaş et al. (2005), and Baümler et al. (2006) re-

Table 4. Volume (V_d), equivalent diameter (D_{ed}), thousand seed mass (W_{1000d}), and sphericity (ϕ_d) of dark chia seeds with different MCs.[a]

MC (% d.b.)	V_d (mm^3)	D_{ed} (mm)	W_{1000d} (g)	ϕ_d (%)
4.6	1.09 ±0.01 a	1.28 ±0.00 a	1.230 ±0.002 a	67.0 ±0.1 a
6.5	1.15 ±0.02 b	1.30 ±0.00 b	1.258 ±0.001 b	67.6 ±0.3 a
8.7	1.18 ±0.01 c	1.31 ±0.00 c	1.274 ±0.002 c	67.2 ±0.2 a
10.0	1.21 ±0.01 c	1.32 ±0.00 c	1.283 ±0.001 c	67.4 ±0.1 a
12.0	1.24 ±0.01 d	1.33 ±0.00 d	1.303 ±0.002 d	67.2 ±0.1 a
15.3	1.27 ±0.00 e	1.34 ±0.00 e	1.327 ±0.003 e	66.7 ±0.4 a
17.7	1.31 ±0.01 f	1.36 ±0.00 f	1.352 ±0.002 f	65.8 ±0.4 a

[a] Mean values ($n = 100$) ± standard deviations. Means in the same column followed by the same letter are not significantly different ($p > 0.05$).

Table 5. Volume (V_w), equivalent diameter (D_{ew}), thousand seed mass (W_{1000w}), and sphericity (ϕ_w) of white seeds with different MCs.[a]

MC (% d.b.)	V_w (mm^3)	D_{ew} (mm)	W_{1000w} (g)	ϕ_w (%)
4.9	1.02 ±0.02 a	1.25 ±0.01 a	1.170 ±0.010 a	65.1 ±0.4 a
5.7	1.05 ±0.07 ab	1.26 ±0.03 a	1.182 ±0.015 b	64.2 ±0.4 a
6.4	1.10 ±0.01 b	1.28 ±0.01 ab	1.212 ±0.002 c	63.2 ±0.3 a
7.9	1.14 ±0.03 bc	1.30 ±0.01 b	1.234 ±0.001 d	63.6 ±0.5 a
10.9	1.17 ±0.01 c	1.31 ±0.00 bc	1.266 ±0.001 e	63.8 ±0.5 a
16.2	1.25 ±0.02 d	1.34 ±0.01 c	1.293 ±0.002 f	64.7 ±0.4 a

[a] Mean values ($n = 100$) ± standard deviations. Means in the same column followed by the same letter are not significantly different ($p > 0.05$).

ported similar linear increases for soybean, cotton, amaranth, fenugreek, and safflower seeds, respectively.

The equivalent diameter (D_e, mm) of both types of chia seeds increased linearly and significantly with the increase in MC. Equivalent diameter increased from 1.28 to 1.36 mm for dark seeds and from 1.25 mm to 1.34 mm for white seeds, representing variations of 6.3% and 7.1%, respectively (tables 4 and 5). These measurements were in the same range as those reported by Ixtaina et al., 2008. The equivalent diameter of seed was found to have the following linear relationship with MC (x, % d.b.):

$$D_{ed} = 1.2588 + 0.0057x \qquad (\mathrm{R}^2 = 0.9698,\ \mathrm{p} < 0.0001) \tag{24}$$

$$D_{ew} = 1.2277 + 0.0075x \qquad (\mathrm{R}^2 = 0.9235,\ \mathrm{p} < 0.0001) \tag{25}$$

The sphericity did not present significant differences ($p > 0.05$) for both types seeds in the range of MCs studied, varying between 65.8% and 67.6% for dark seeds and between 63.2% and 65.1% for white seeds.

The thousand seed mass of dark chia seeds increased from 1.230 to 1.352 g as the MC of seed increased from 4.6% to 17.8% d.b. We found a similar trend for white chia seeds, which increased from 1.170 to 1.293 g as a function of MC. The average W_{1000} was 1.290 and 1.226 g for dark and white chia seeds, respectively. Statistical analysis showed significant differences ($p \leq 0.05$) for this parameter between seeds with different MCs for both colors (tables 4 and 5). The values of the thousand seed mass (W_{1000}, g) for chia seeds presented the following relationship with MC (x, % d.b.):

$$W_{1000d} = 0.1195 + 0.0009x \qquad (\mathrm{R}^2 = 0.9923,\ \mathrm{p} < 0.0001) \tag{26}$$

$$W_{1000w} = 0.1653 + 0.0089x \qquad (\mathrm{R}^2 = 0.9012,\ \mathrm{p} < 0.0001) \tag{27}$$

Experimental data showed that the linear increase of W_{1000} with MC is quite similar to results reported by Altuntaş et al. (2005) for fenugreek, Gupta and Das (1997) for sunflower, Özarslan (2002) for cotton, Singh and Goswami (1996) for cumin, and Vilche et al. (2003) for quinoa.

The experimental results of the effect of MC on the static coefficient of friction of dark chia seeds against two surfaces (galvanized iron and aluminum) are shown in figure 4. It is evident that the static coefficient of friction increased linearly with an increase in MC for both contact surfaces. The reason for the increased friction coefficient at higher MCs may be that the water present in the seed offered a cohesive force on the contact surface. We recorded increments of 28.4% and 29.5% for the galvanized iron and aluminum surfaces, respectively, as the MC increased from 4.6% to 17.7% (d.b.). At all MCs, the friction caused by the aluminum surface was slightly higher than that presented by the galvanized iron surface.

The relationship between static coefficient of friction and MC on galvanized iron (*gi*) and aluminum (*al*) surfaces can be represented by the following equations:

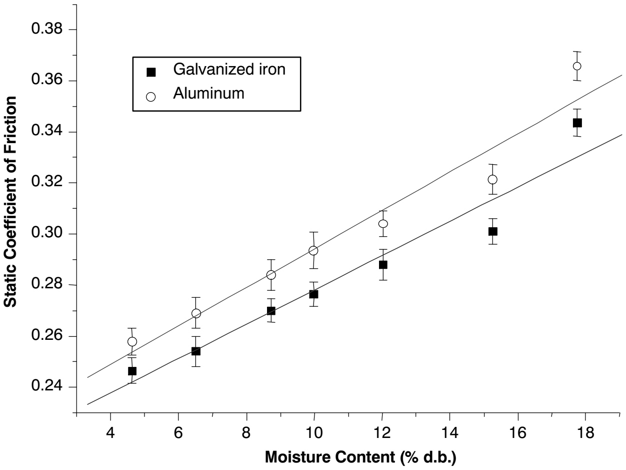

Figure 4. Effect of MC on the coefficient of static friction of chia seeds determined on galvanized iron and aluminum surfaces.

$$\mu_{gi} = 0.2096 + 0.0068x \qquad (\mathrm{R}^2 = 0.9417,\ \mathrm{p} < 0.0005) \tag{28}$$

$$\mu_{al} = 0.2189 + 0.0075x \qquad (\mathrm{R}^2 = 0.9496,\ \mathrm{p} < 0.0005) \tag{29}$$

Singh and Goswami (1996) and Coşkun et al. (2006) reported similar trends for sweet corn and cumin, respectively.

CONCLUSIONS

Most of the physical properties of chia seeds showed changes in the range of MC studied. The results obtained showed that the characteristic axial dimensions increased linearly with no significant differences between types of seed (dark and white). The geometric diameter, specific surface area, volume, equivalent diameter, and thousand seed mass followed similar trends, increasing linearly with the increase of MC for all chia seeds. The sphericity did not present significant differences for both types of seed in the range of MC studied. The true density diminished linearly in the range of MCs for dark and white chia seeds. The bulk density and porosity varied nonlinearly for dark seeds, showing a quadratic concave behavior as a function of MC. The static coefficient of friction on galvanized iron and aluminum surfaces for dark chia seeds increased as MC increased from 4.6% to 17.7% (d.b.).

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NOMENCLATURE

D_e = equivalent diameter (mm)
D_g = geometric diameter (mm)
d.b. = dry basis
d, w = subscripts used to differentiate values corresponding to dark and white chia seeds, respectively
L = length of seed (mm)
m = unit mass of seed (g)
S = specific surface area (mm^2)
T = thickness (mm)
V = seed volume (mm^3)
W = width of seed (mm)
W_{1000} = thousand seed mass (g)
x = moisture content (% d.b.)
α = angle of tilt (degrees)
ε = porosity of seed (%)
ϕ = sphericity of seed (%)
μ = static coefficient of friction (dimensionless)
ρ_b = bulk density (g cm^{-3})
ρ_t = true density (g cm^{-3})